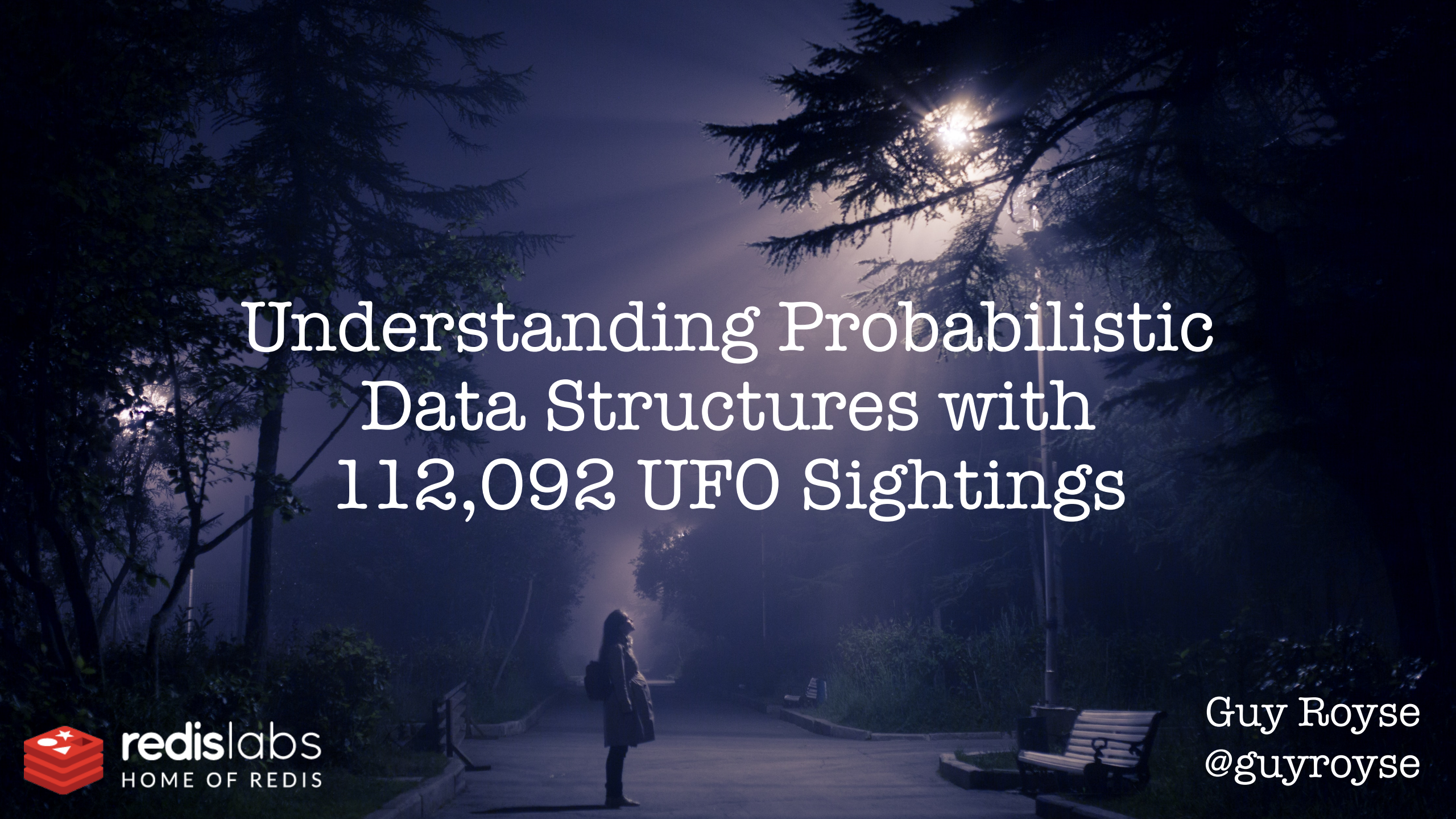

Understanding Probabilistic
Data Structures with
112,092 UFO Sightings
redislabs
HOME OF REDIS
Guy Royse
@guyroyse

redislabs
HOME OF REDIS

Guy Royse
Developer Advocate
Redis Labs

@guyroyse
github.com/guyroyse
guy.dev

112,092

Key	Value
summary	Three saucer shaped ships. High in the sky, metallic but no shine. Rather dull gray. They hovered overhead in a V formation.
city	Salem
state	Oregon
date_time	1950-09-15T14:00:00-07:00
shape	disk
duration	15 minutes
report_link	http://www.nuforc.org/webreports/135/S135871.html
text	Three saucer shaped ships. High in the sky, metallic but no shine. Rather dull gray. They hovered overhead in a V formation and from time to time seemed to dip down and they had a bubble shaped top. (NUFORC Note: Witness indicates that the date above is approximate. PD)
city_latitude	44.941247110675775
city_longitude	-123.00423516160726

What's a Probabilistic Data Structure?

Guy Royse
@guyroyse

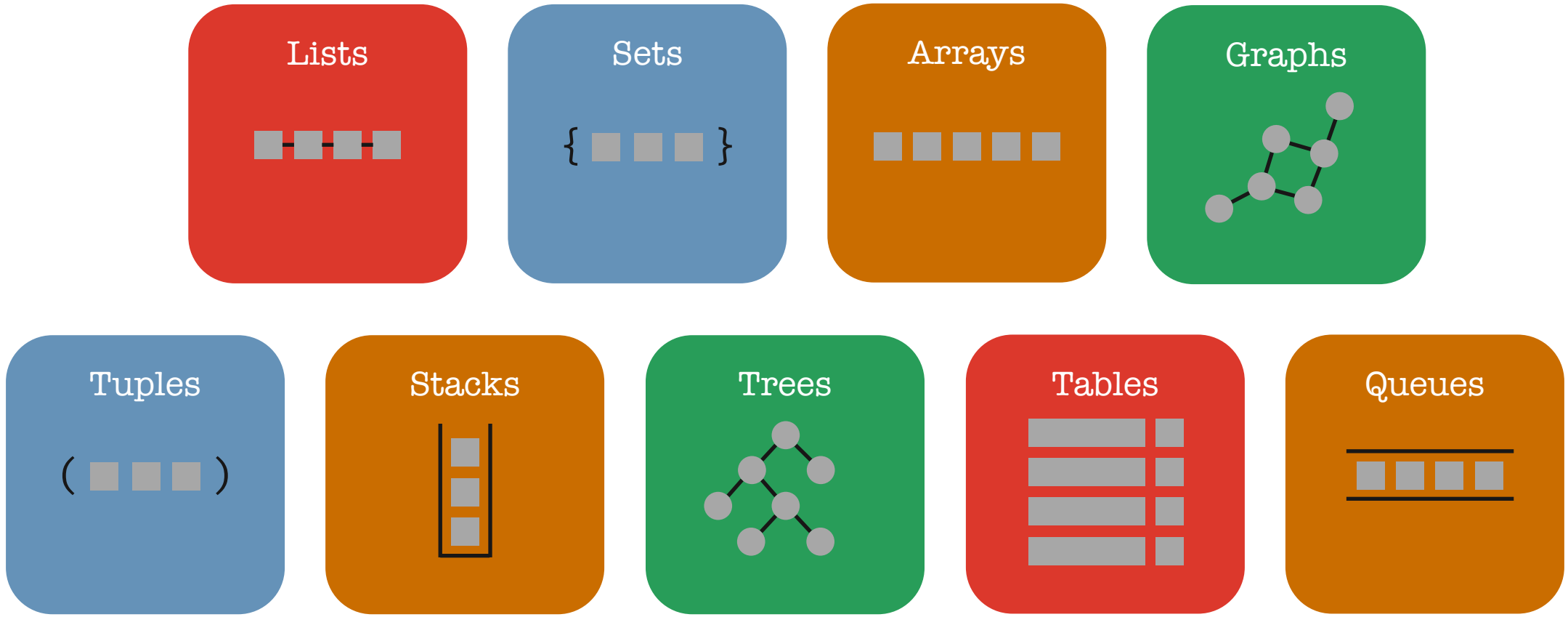
Quick developer survey. Have you heard of probabilistic data structures?

Never heard of 'em.	**58%**
I've heard the term.	22%
I know what they are.	9%
I've used them.	11%

119 votes · Final results

5:34 PM · Dec 12, 2019 · Twitter Web App

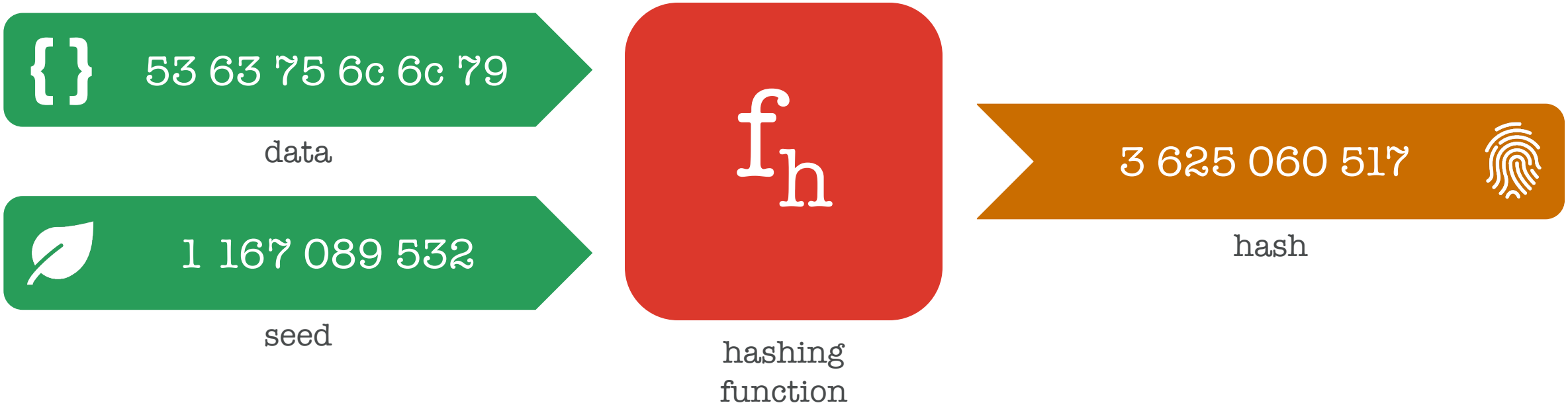
Deterministic Data Structures



Hash Table

Key	Value
city	Salem
state	Oregon
date_time	1950-09-15T14:00:00-07:00
shape	disk
summary	Three saucer shaped ships. High in the sky, metallic but no shine. Rather dull gray. They hovered overhead in a V formation.

Hashing Functions



Adding to a Hash Table

Index	Bucket
0	
1	“Salem”
2	
3	
4	
5	
6	
7	
8	
9	

Adding to a Hash Table

Index	Bucket
0	
1	“Salem”
2	
3	
4	“Oregon”
5	
6	
7	
8	
9	

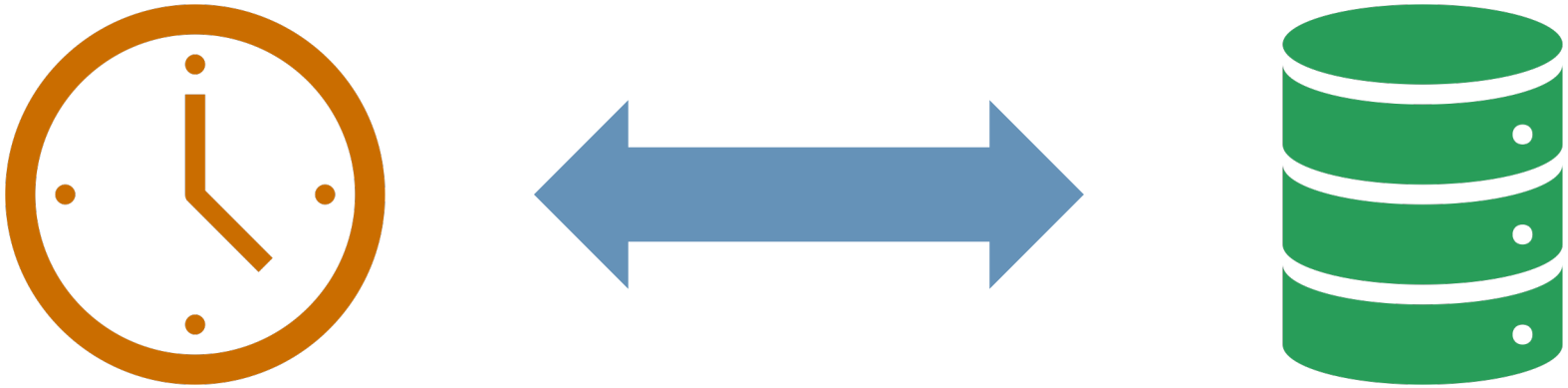
Hash Collisions

Index	Bucket
0	
1	“Salem”, “disk”
2	
3	
4	“Oregon”
5	
6	
7	
8	
9	

Reading from a Hash Table

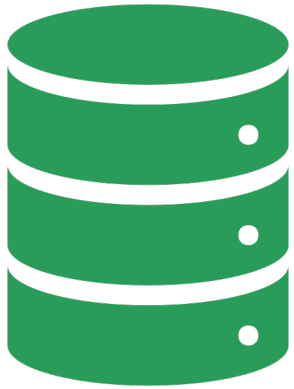
Index	Bucket
0	
1	“Salem”, “disk”
2	
3	
4	“Oregon”
5	“1950-09-15T14:00:00-07:00”
6	
7	“Three saucer shaped ships…”
8	
9	

Time & Space Complexity



Time & Space Complexity

Time

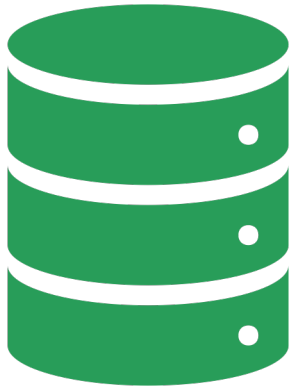


Space

Accuracy Complexity

Time

Accuracy



Space

Hash Table without Chaining (Probably a Bad Idea)

Index	Bucket
0	
1	“Salem”
2	
3	
4	“Oregon”
5	“1950-09-15T14:00:00-07:00”
6	
7	“Three saucer shaped ships…”
8	
9	

Hash Collisions (Definitely a Bad Idea)

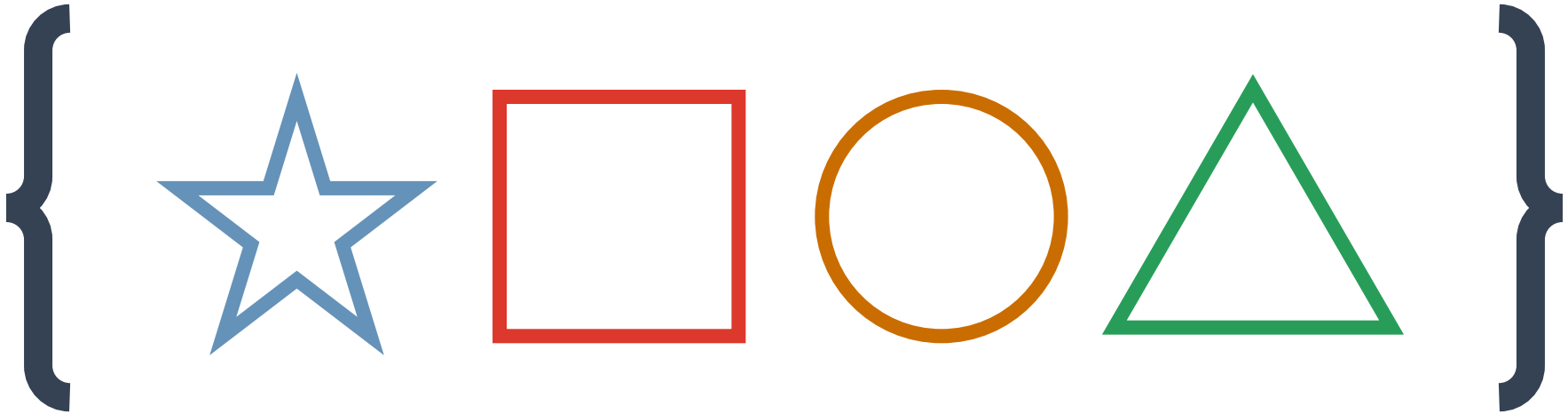
Index	Bucket
0	
1	“disk”
2	
3	
4	“Oregon”
5	“1950-09-15T14:00:00-07:00”
6	
7	“Three saucer shaped ships…”
8	
9	

Reading from It (OMG! What Have I done?)

Index	Bucket
0	
1	“disk”
2	
3	
4	“Oregon”
5	“1950-09-15T14:00:00-07:00”
6	
7	“Three saucer shaped ships…”
8	
9	

A Little Bit Lossy But Good Enough

Many probabilistic data structures can be though of as peculiar sets.

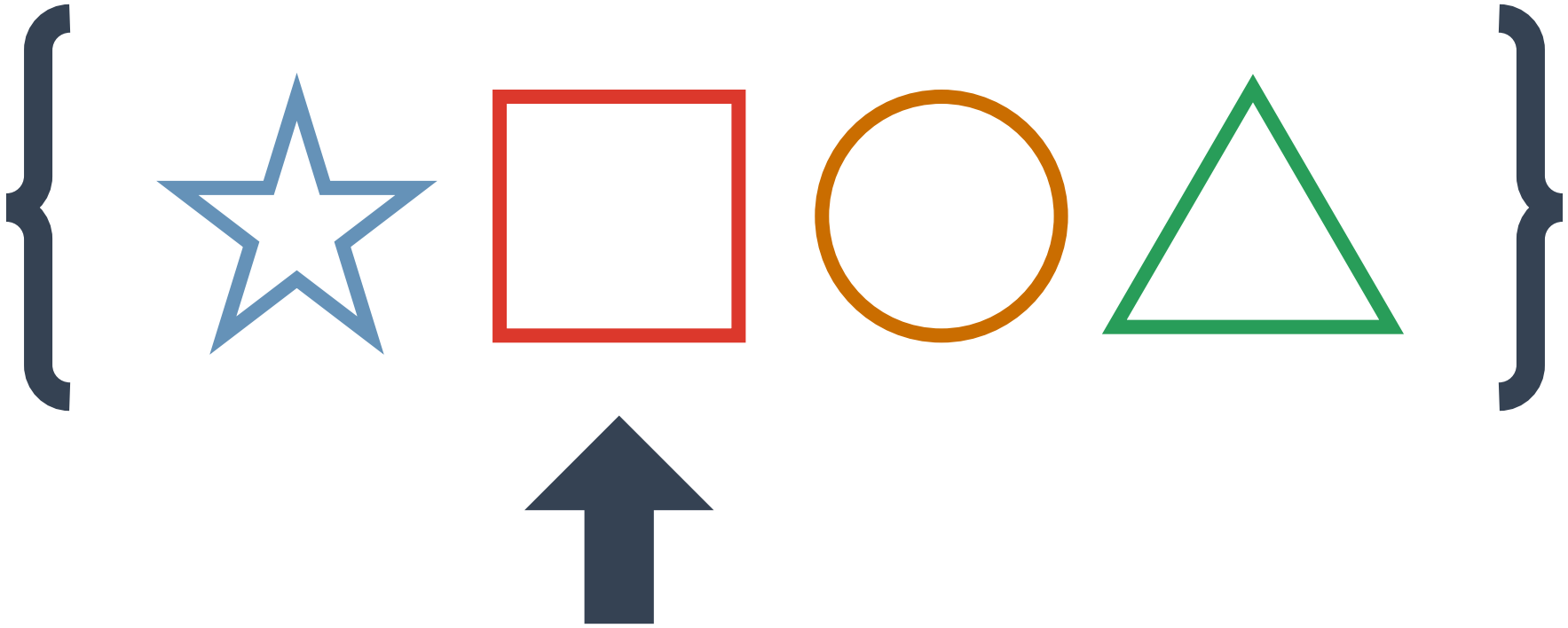


Add · Remove · Get · Union · Intersect · Difference · Membership · Cardinality

Membership

Is the thing in the set?

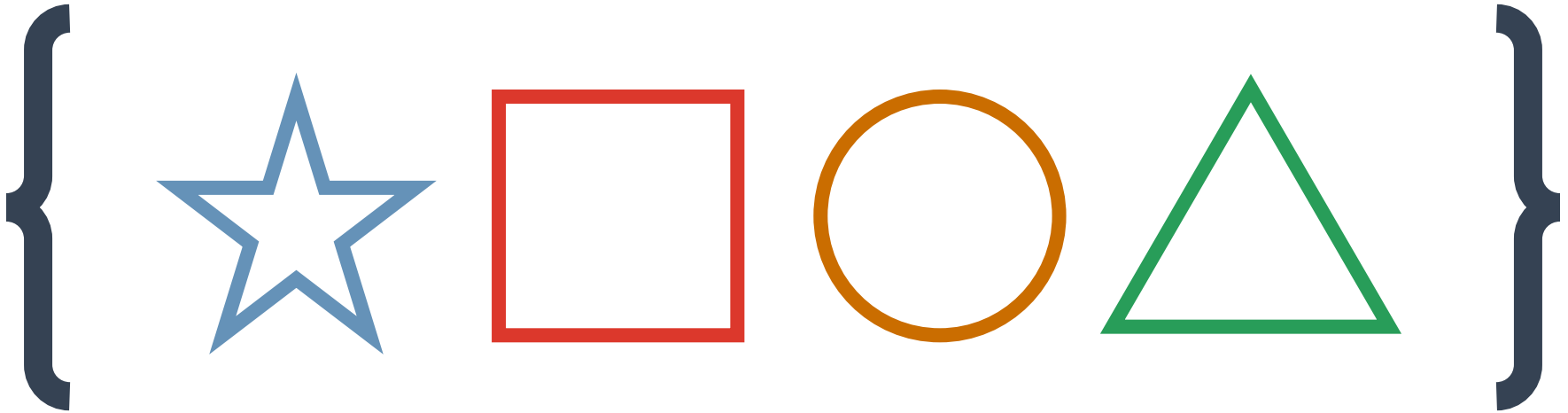
A member is any one of the distinct objects that make up a set.



Cardinality

How many of the thing are in the set?

The number of members in a set.

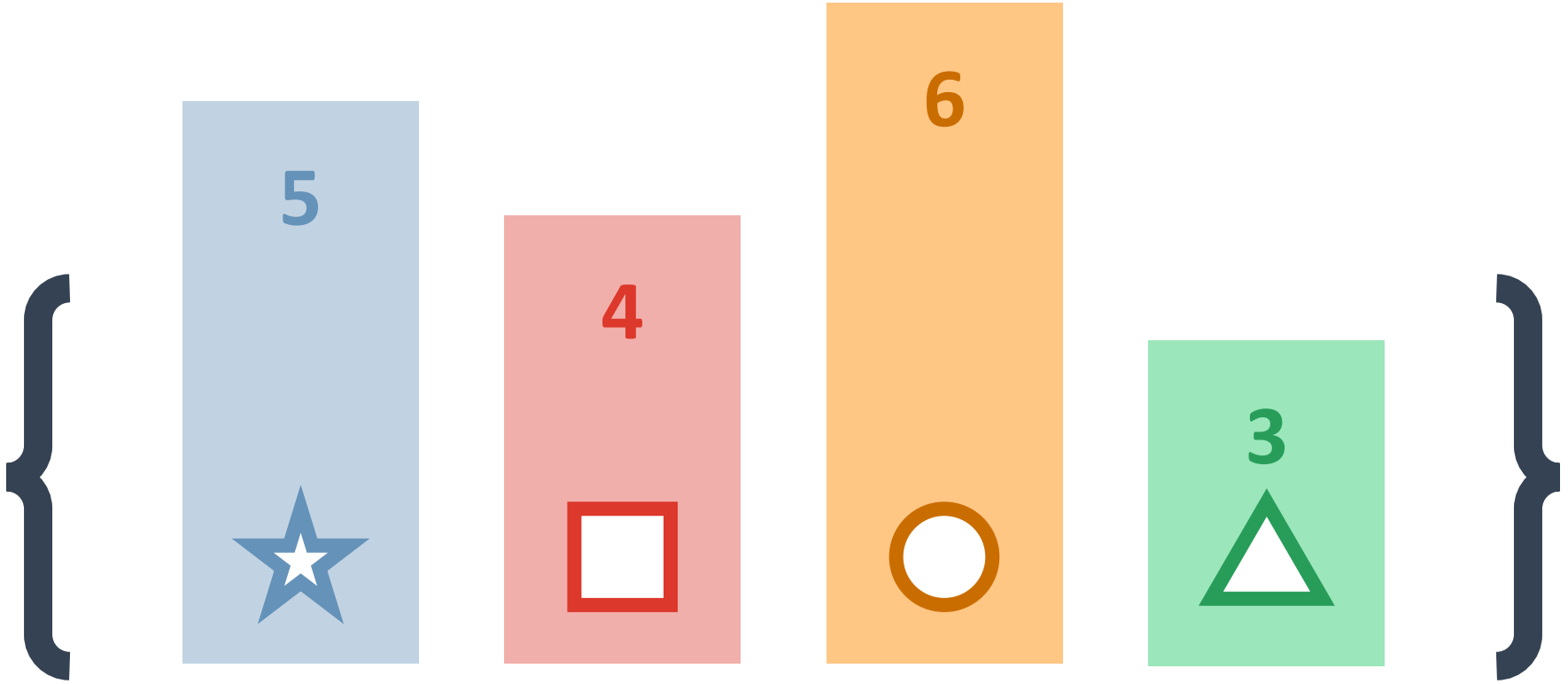


1 2 3 4

Frequency

How many of each thing is in the set?

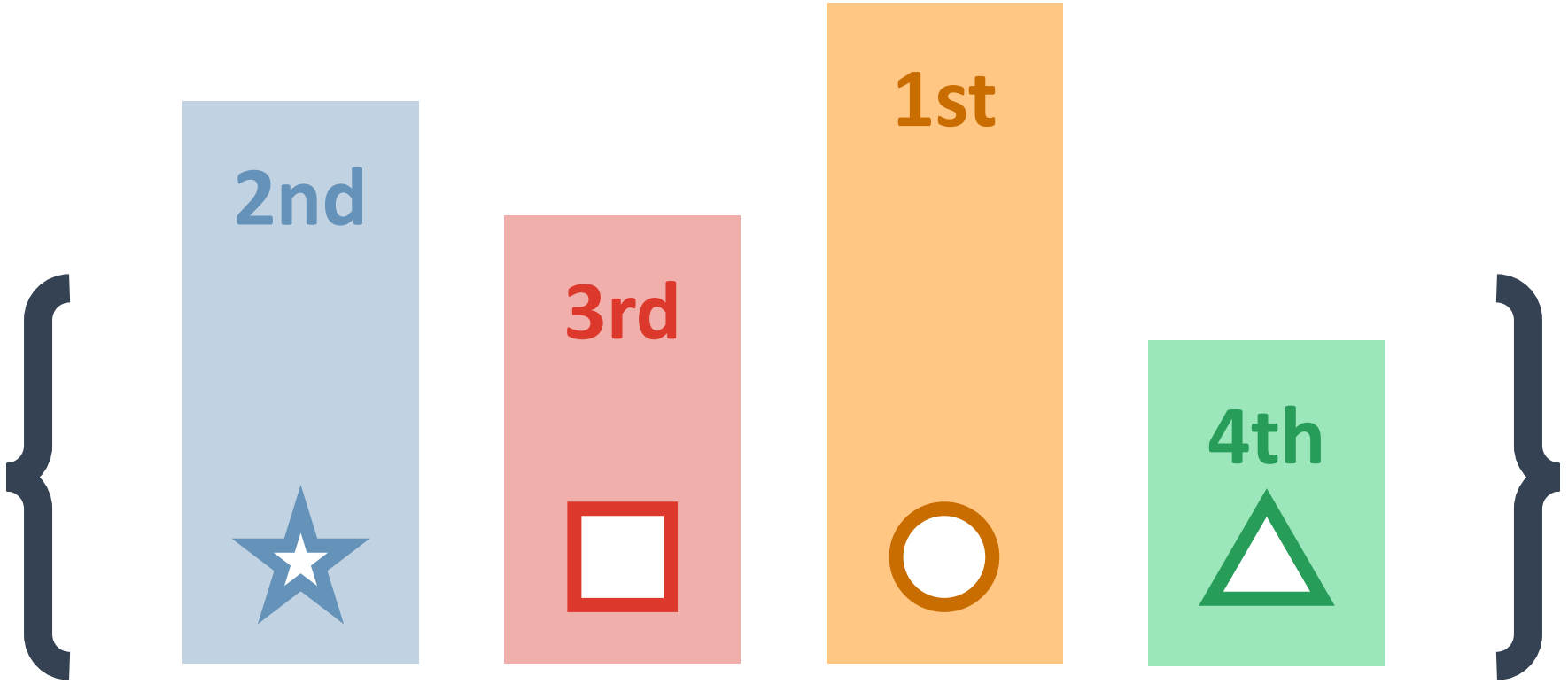
The number of times a member is found in a set.



Rank

Where does
the thing
belong
in the set?

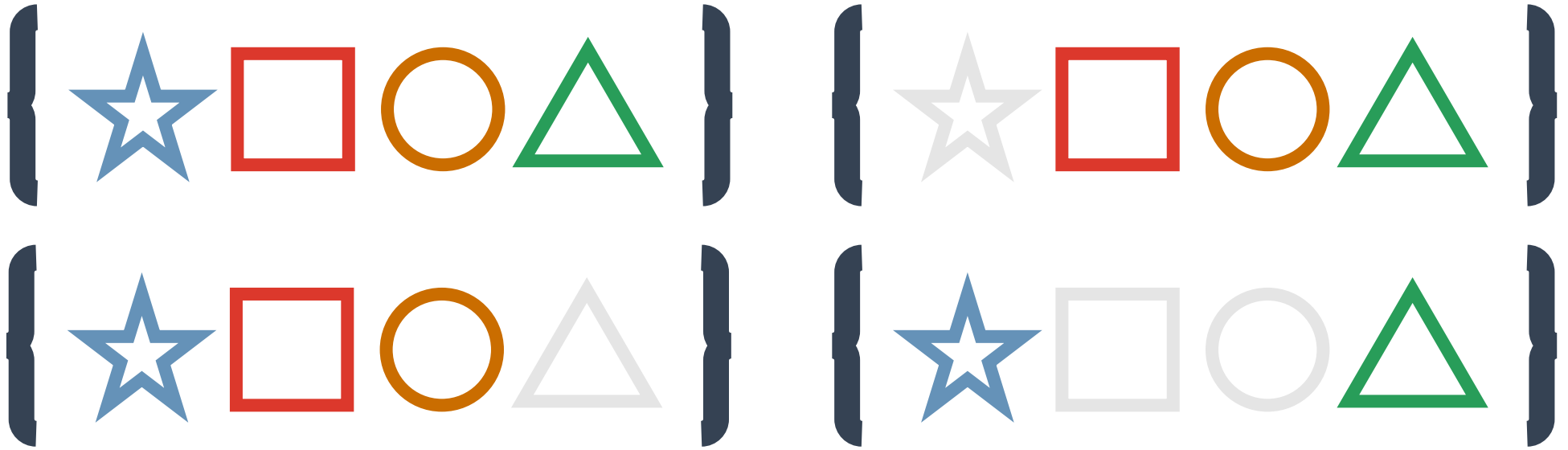
The position of a member of a set relative to other members.



Similarity

Is the thing like the other things?

A measure of the differences between sets.



Lots of Choices

Name	Usage
Bloom Filter†	Membership
Cuckoo Filter†	Membership
HyperLogLog‡	Cardinality
Count Sketch	Frequency
Count-Min Sketch†	Frequency
Q-digest	Rank
T-digest	Rank
Heavy Keeper†	Rank
Heavy Guardians	Rank
MinHash	Similarity
SimHash	Similarity

‡ included with Redis † included with RedisBloom

Redis Modules

Bloom Filter*

What's a Bloom Filter?

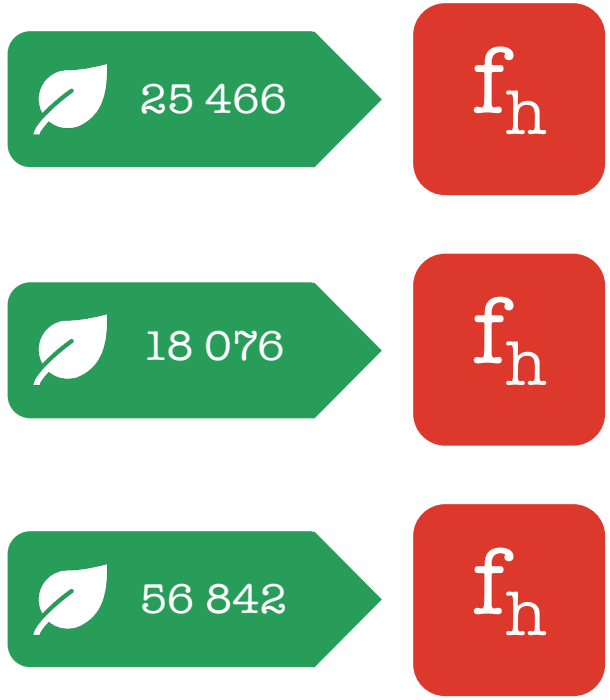
Membership:
No or Probably

Fixed Size

Fast

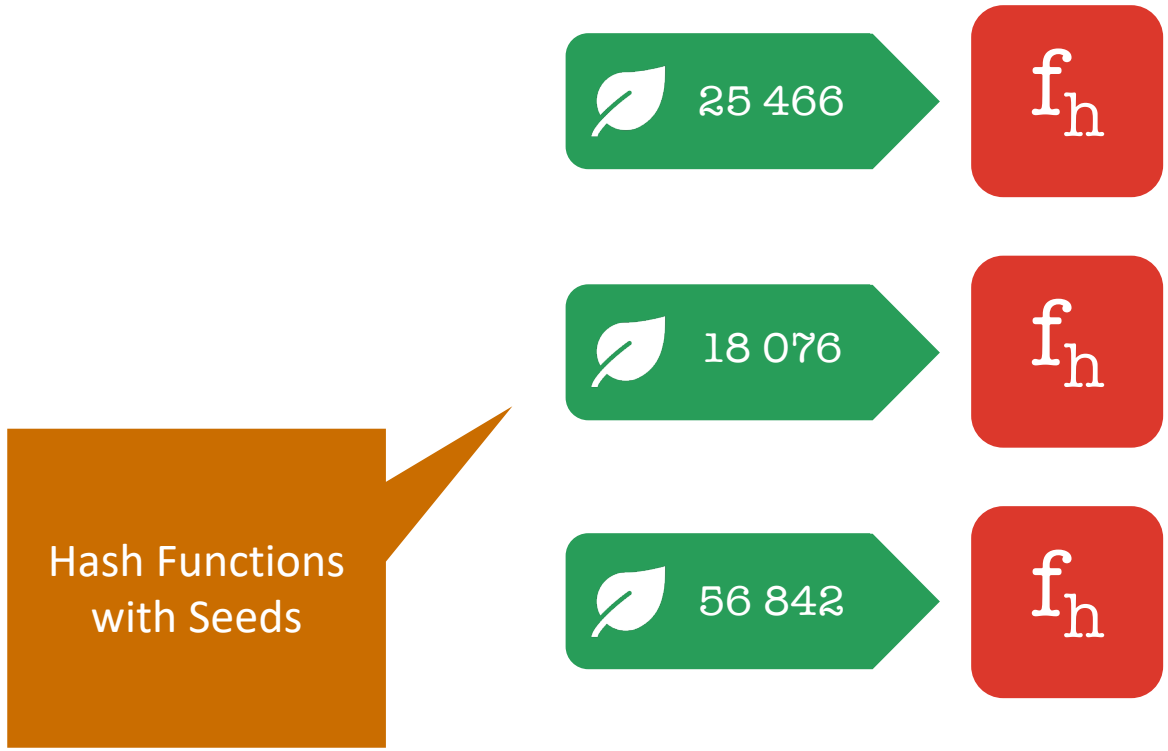
Parts of a Bloom Filter

Bit	0	0	0	0	0	0	0	0	0	0
Index	0	1	2	3	4	5	6	7	8	9



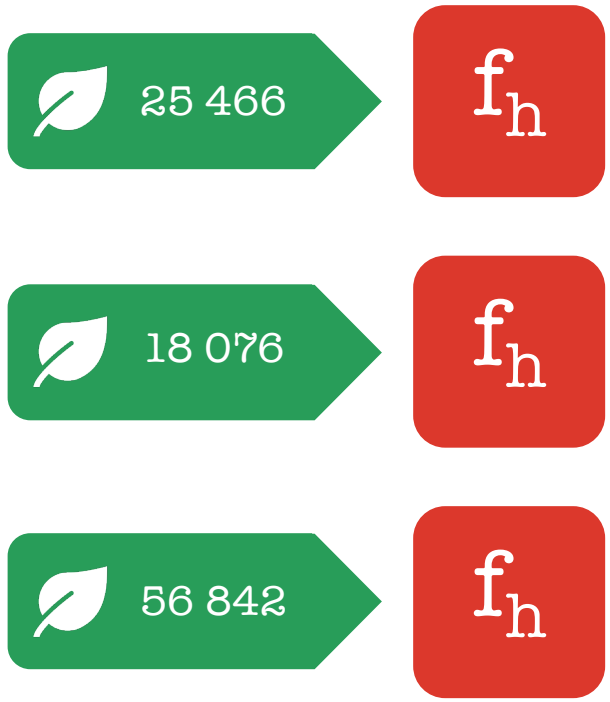
Parts of a Bloom Filter

Bit	0	0	0	0	0	0	0	0	0	0
Index	0	1	2	3	4	5	6	7	8	9



Parts of a Bloom Filter

Bit	0	0	0	0	0	0	0	0	0	0
Index	0	1	2	3	4	5	6	7	8	9

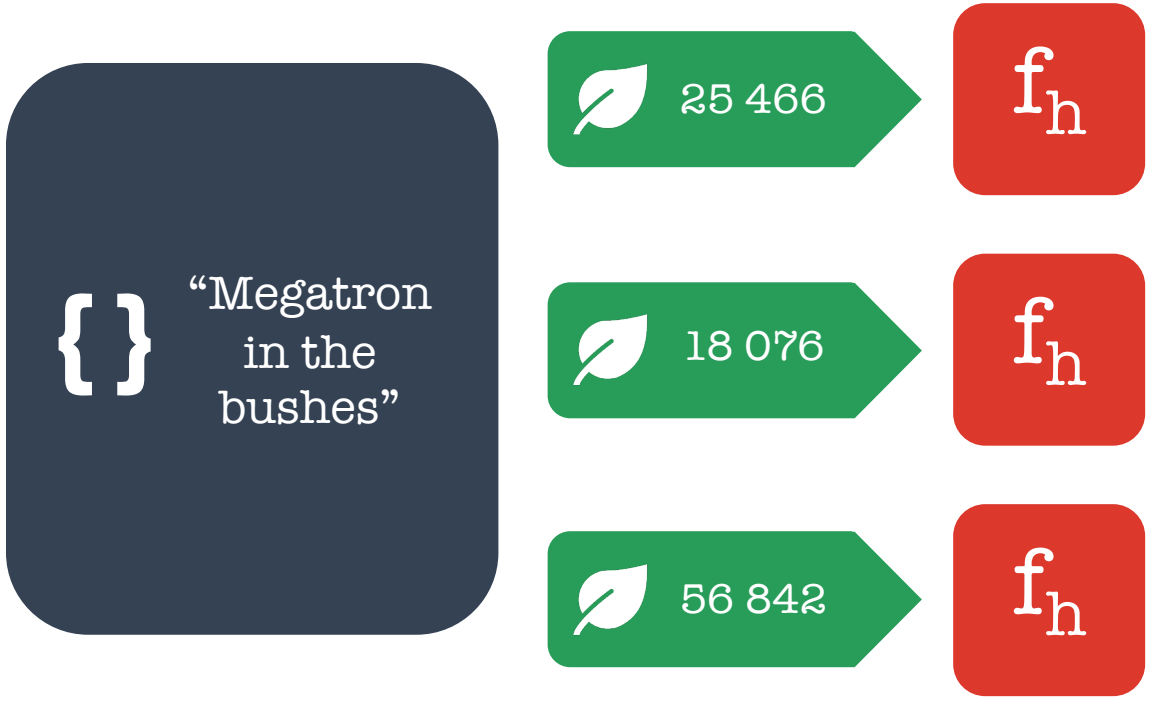


Bit Array of Fixed Width

Hash Functions with Seeds

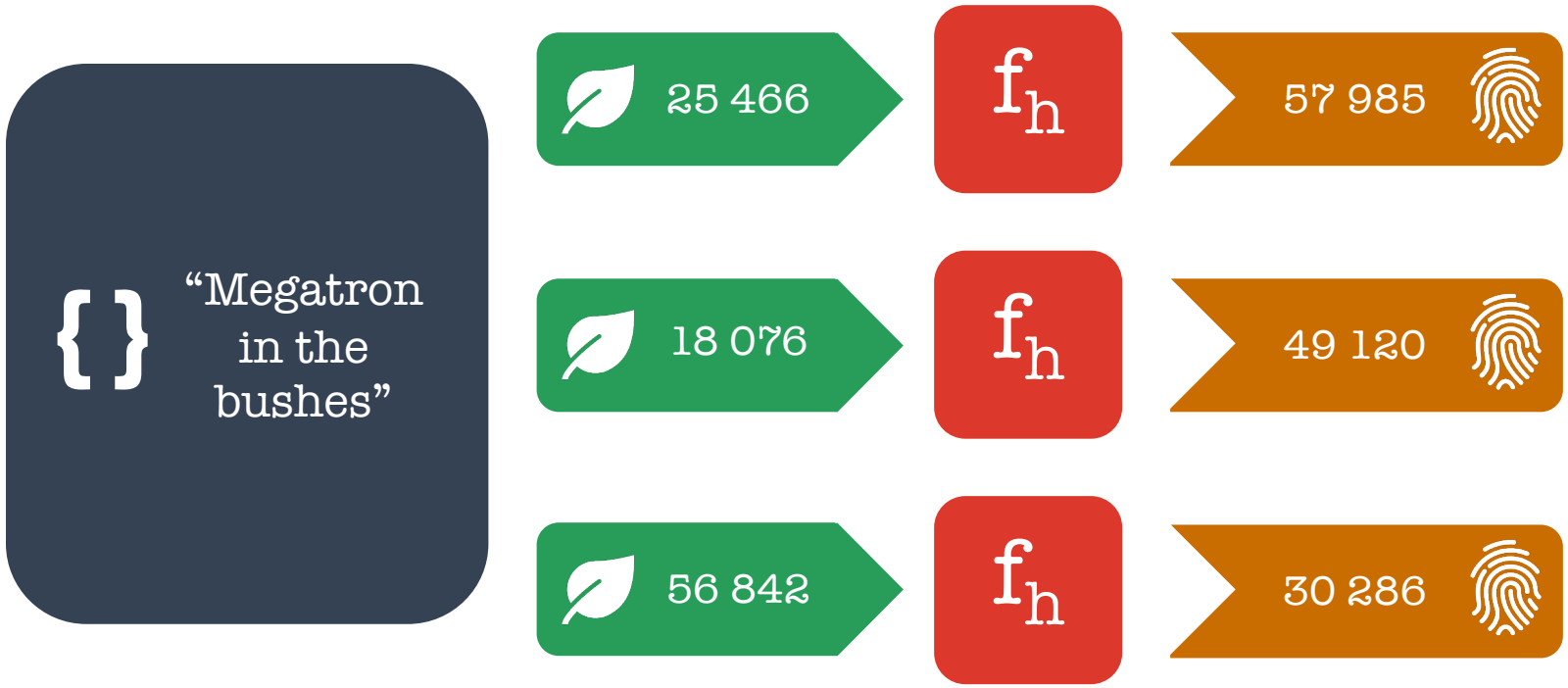
Adding to a Bloom Filter

Bit	0	0	0	0	0	0	0	0	0	0
Index	0	1	2	3	4	5	6	7	8	9



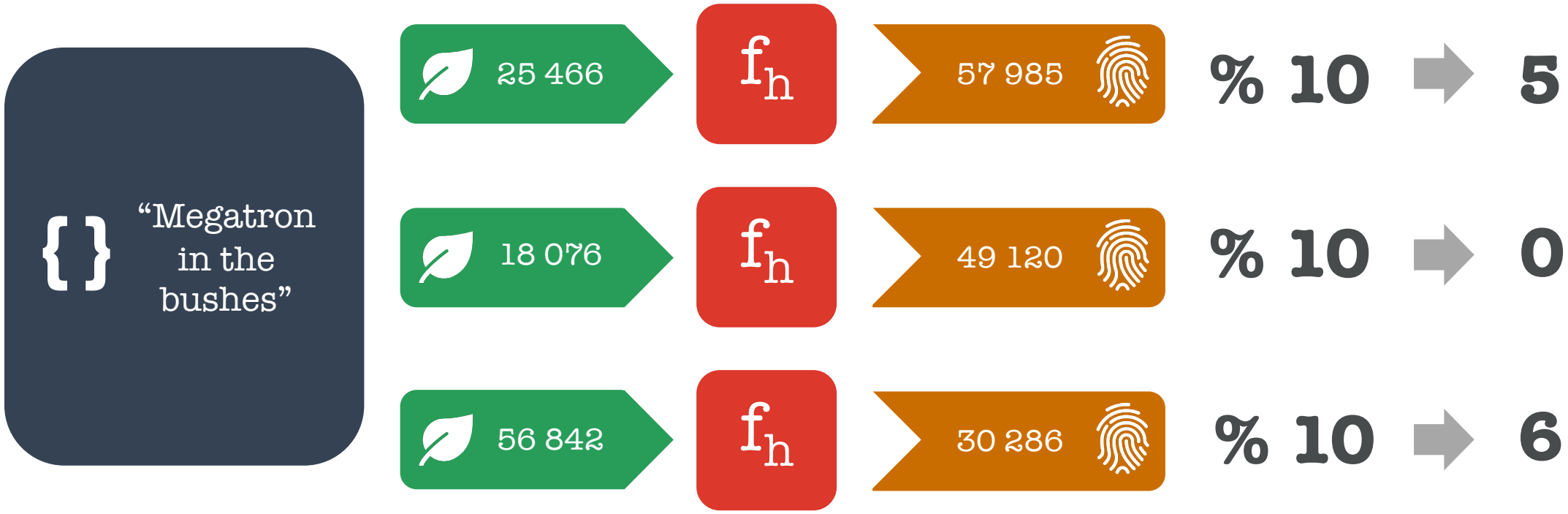
Adding to a Bloom Filter

Bit	0	0	0	0	0	0	0	0	0	0
Index	0	1	2	3	4	5	6	7	8	9



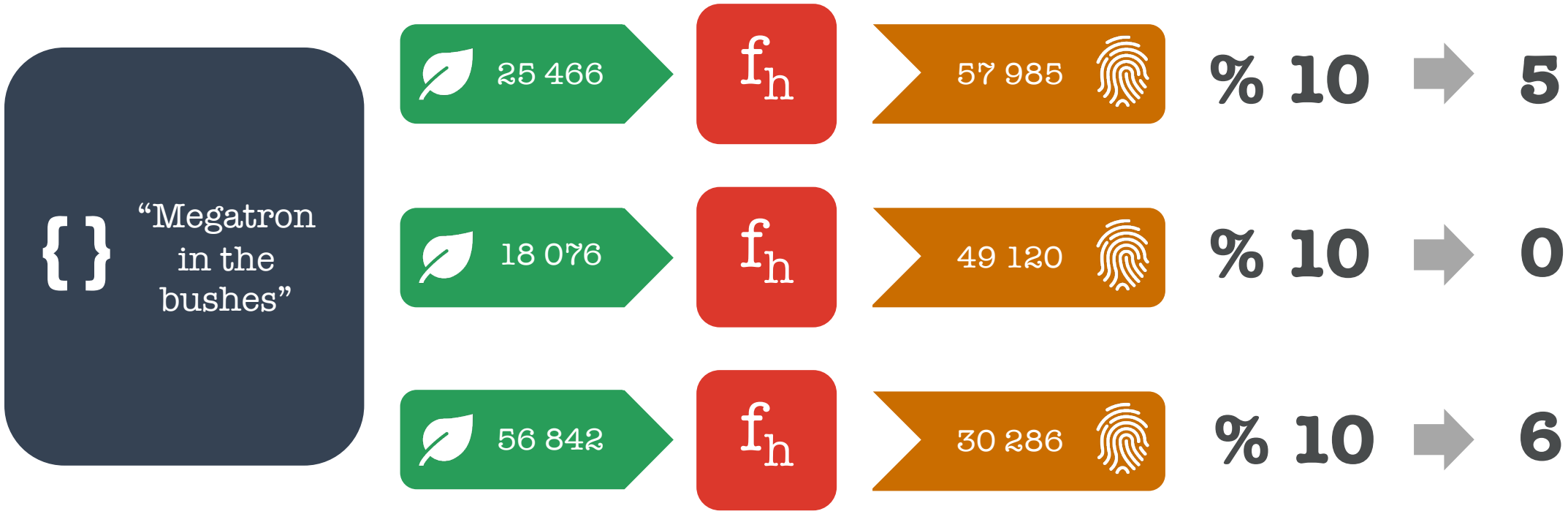
Adding to a Bloom Filter

Bit	0	0	0	0	0	0	0	0	0	0
Index	0	1	2	3	4	5	6	7	8	9



Adding to and Reading from Bloom Filter

Bit	1	0	0	0	0	1	1	0	0	0
Index	0	1	2	3	4	5	6	7	8	9



Adding to and Reading from a Bloom Filter with Collision

Bit	1	1	1	0	0	1	1	0	0	0
Index	0	1	2	3	4	5	6	7	8	9

{ } "I SEEN A UFO WHEN I WAS ABOUT 13 YEARS OLD"

25 466 → f_h → 50 062 → % 10 → 2

18 076 → f_h → 23 121 → % 10 → 1

56 842 → f_h → 45 106 → % 10 → 6

Adding to and Reading from a Bloom Filter with Total Collision

Bit	1	1	1	0	0	1	1	0	0	0
Index	0	1	2	3	4	5	6	7	8	9

{ } "Investig-ators from the BFRO observed a glowing green/blue sphere"

25 466 → f_h → 23 150 → % 10 → 0

18 076 → f_h → 39 361 → % 10 → 1

56 842 → f_h → 63 416 → % 10 → 6

Computing Hashes & Width

$$p = \left(1 - e^{-kn/mk}\right)^k$$

$$k = ({}^{m}/_{n}) \cdot \ln(2)$$

- $n \rightarrow$ number of items
- $m \rightarrow$ number of bits
- $k \rightarrow$ number of hashes
- $p \rightarrow$ false positive rate

Using Bloom Filters in Redis

>	BF.RESERVE	ufo:shapes	0.005	100
	command	key	Error rate	Capacity
OK				

Adding to Bloom Filters in Redis

>	BF.ADD	ufo:shapes	disk
	command	key	Item to add

```
(integer) 1
```

>	BF.ADD	ufo:shapes	light
	command	key	Item to add

```
(integer) 1
```

>	BF.MADD	ufo:shapes	light	teardrop
	command	key	Item to add	Another item to add

```
(integer) 0
(integer) 1
```

Using a Bloom Filters in Redis

```
> BF.EXISTS ufo:shapes disk
    command   key       Item to add
(integer) 1
```

```
> BF.EXISTS ufo:shapes light
    command   key       Item to add
(integer) 1
```

```
> BF.MEXISTS ufo:shapes light  triangle
    command    key       Item to add  Another item to add
(integer) 1
(integer) 0
```

MinHash

What's a MinHash?

Determines
Set Similarity
Between
Documents

Jaccard Similarity

California
Nevada
Oregon
Wyoming

New Mexico
Ohio

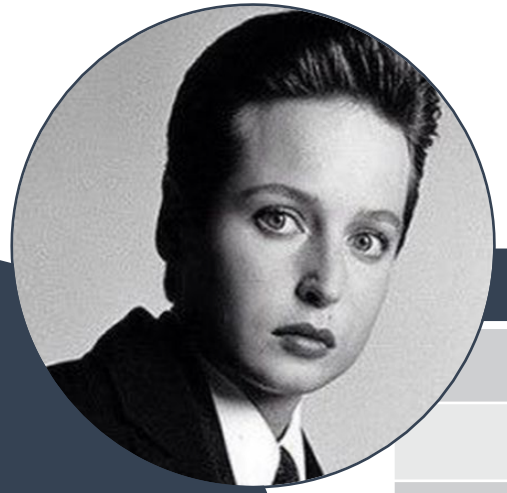
Florida
Kansas
South Carolina
West Virginia

Intersection	2
Union	10
Jaccard Similarity	**2 / 10 = 0.2**

Shingling: Turning Documents into Sets

We noticed to our left, farther off into the mountains, a bright glow.

Shingles
we noticed to
noticed to our
to our left
our left farther
left farther off
farther off into
off into the
into the mountains
the mountains a
mountains a bright
a bright glow



Sculder's Report
we noticed to
noticed to our
to our left
our left farther
left farther off
farther off into
off into the
into the mountains
the mountains a

Mully's Report
to our left
our left farther
left farther off
farther off into
off into the
into the mountains
the mountains a
mountains a bright
a bright glow

Intersection	7
Union	11
Jaccard Similarity	**7 / 11 = 0.636**

Calculating Sculder's MinHash

Sculder's Report
we noticed to
noticed to our
to our left
our left farther
left farther off
farther off into
off into the
into the mountains
the mountains a

f_h → 325 489 646 427 475 722 391 **233** 312 → **233**

f_h → 316 782 907 **143** 459 269 912 419 717 → **143**

f_h → 991 729 534 790 407 **102** 757 174 336 → **102**

Calculating Mully's MinHash

Mully's Report
to our left
our left farther
left farther off
farther off into
off into the
into the mountains
the mountains a
mountains a bright
a bright glow

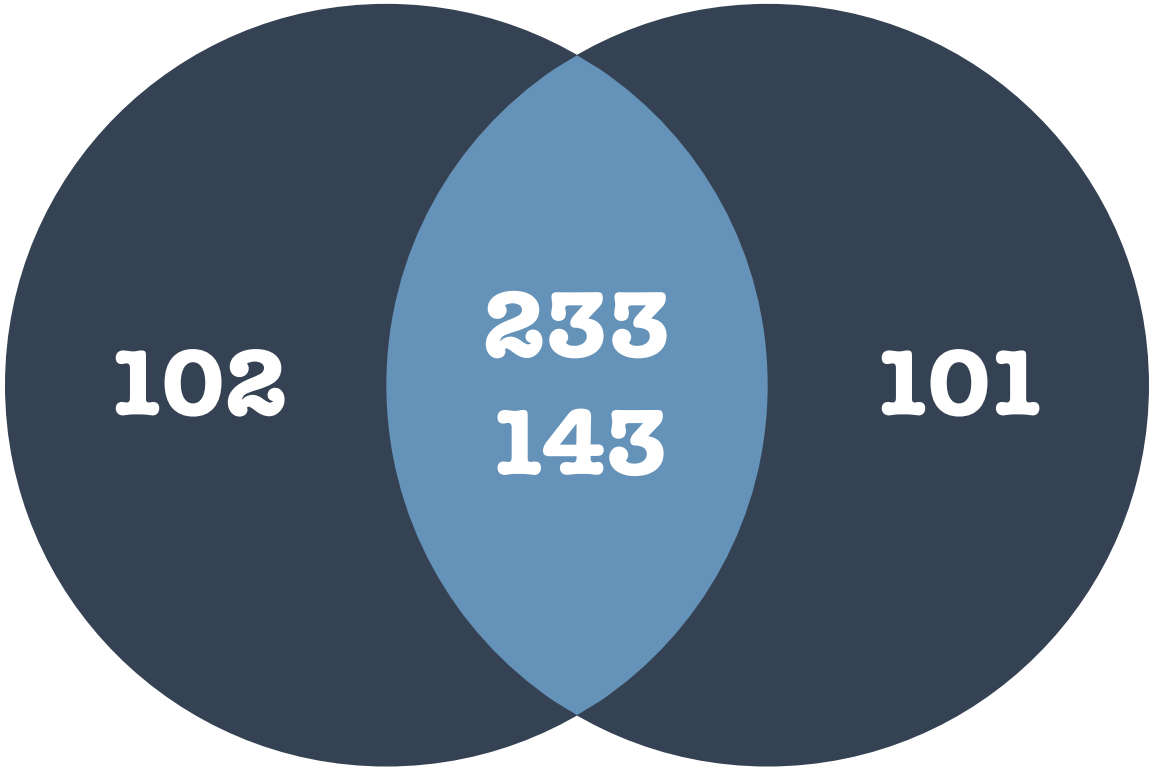
f_h → 646 427 475 722 391 **233** 312 676 891 → **233**

f_h → 907 **143** 459 269 912 419 717 224 315 → **143**

f_h → 534 790 407 102 757 174 336 **101** 865 → **101**

Jaccard Similarity of the Minimum Hashes

233
143
102



233
143
101

Intersection	2
Union	4
Jaccard Similarity	**2 / 4 = 0.5**

Comparing the Results

0.636 vs 0.500

TopK*

(actually Heavy Keeper)

What's a TopK Heavy Keeper?

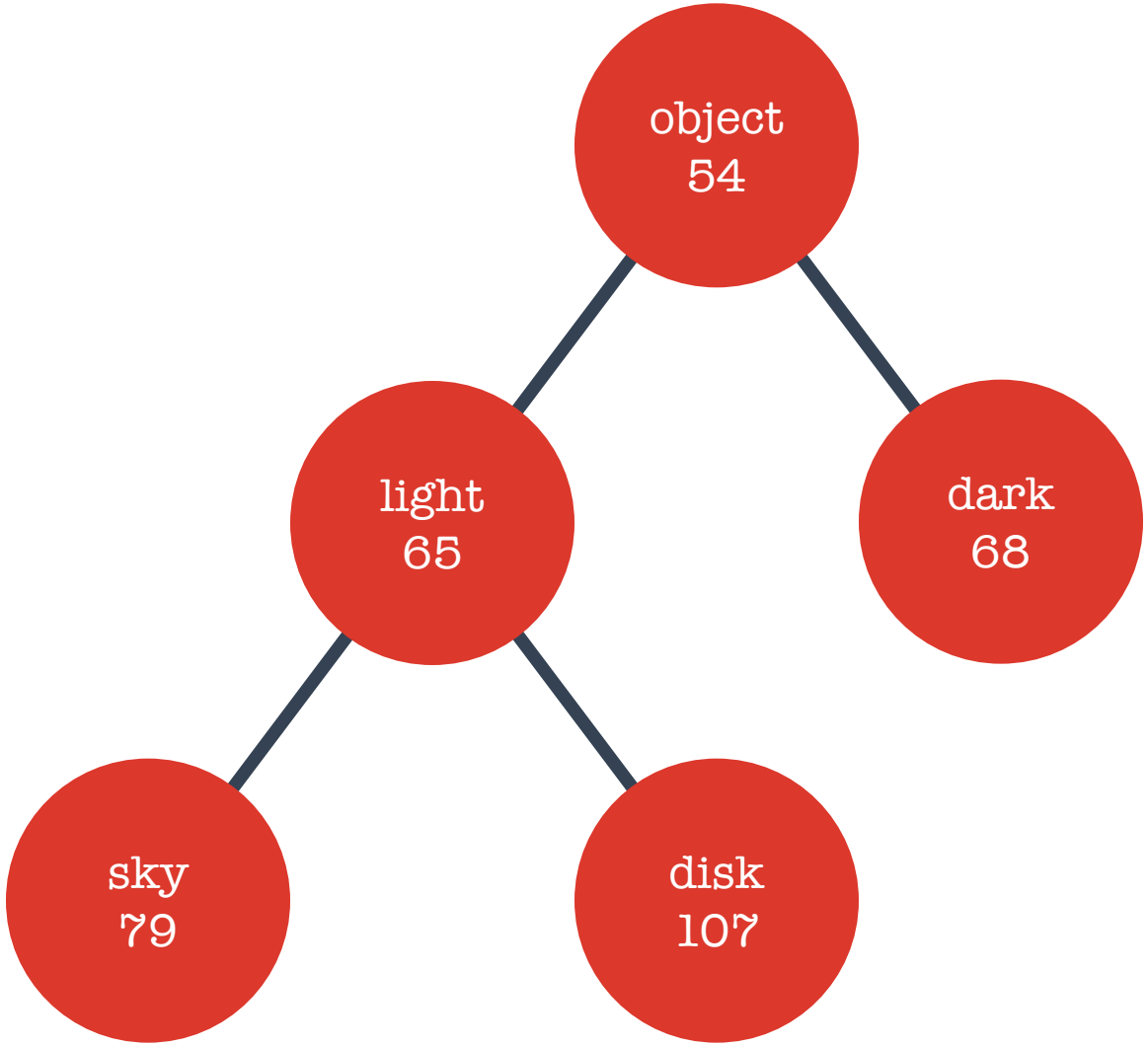
Ranks

Top k

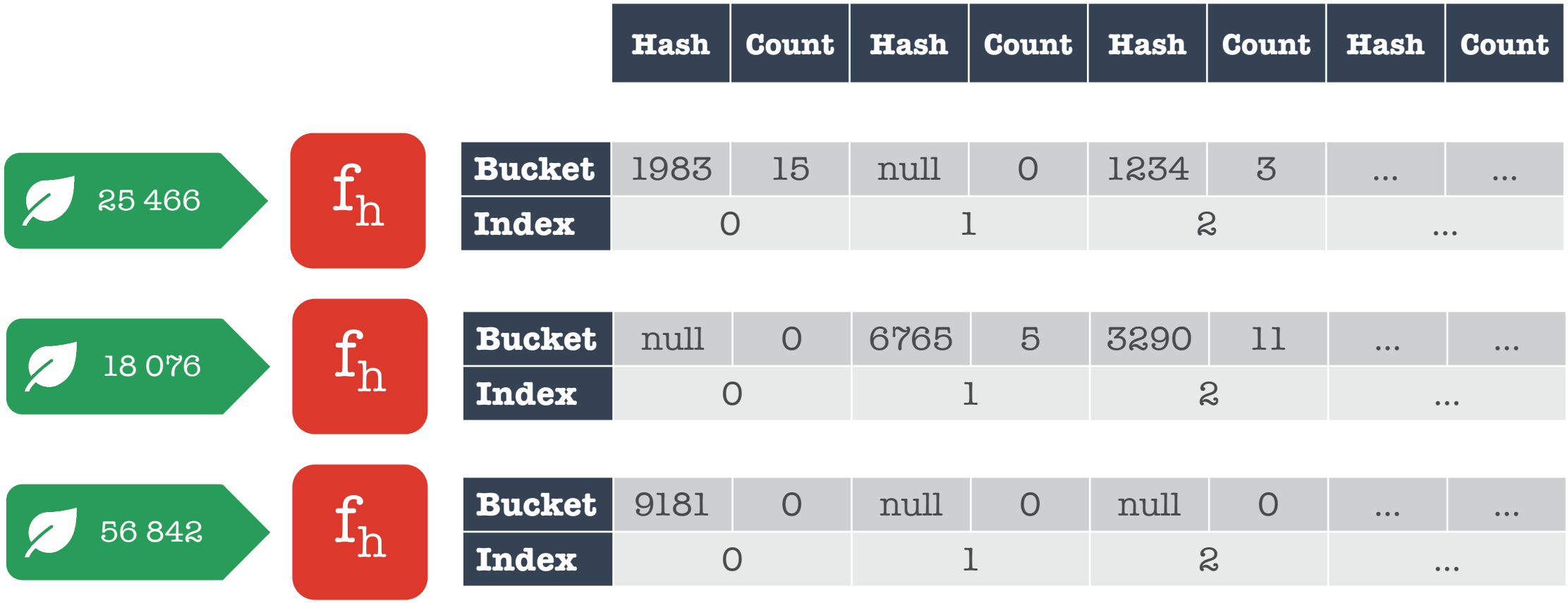
Items

Two Parts

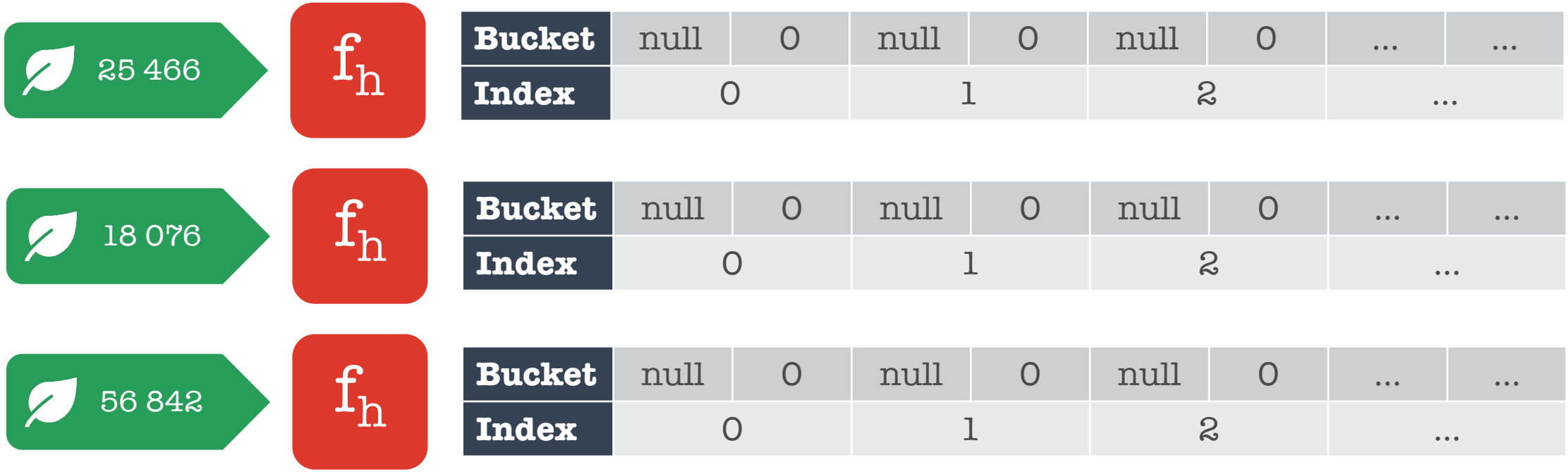
MinHeap



Parts of a Heavy Keeper



Brand New Heavy Keeper



Adding a Value

"object"

f_h 5062 % w → 2

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	null	0	...	...
Index	0		1		2		...	

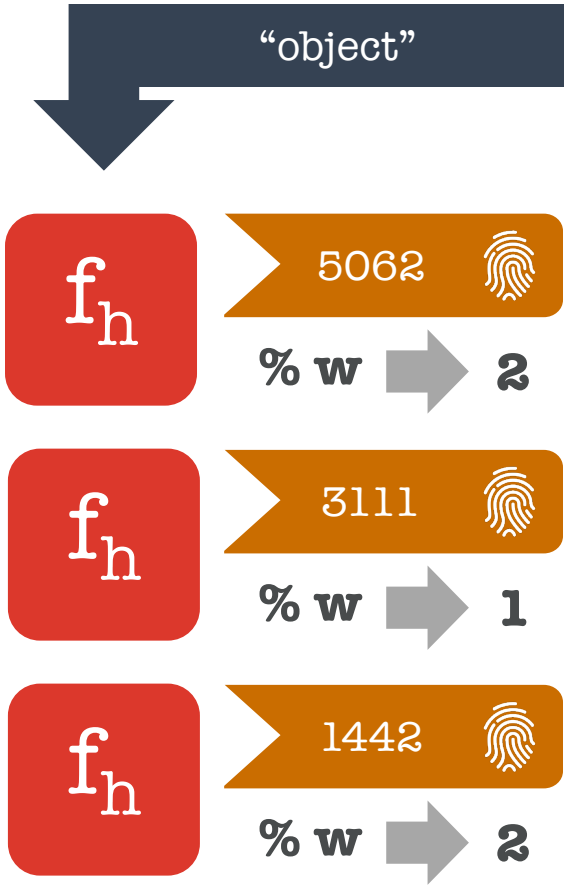
f_h 3111 % w → 1

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	null	0	...	...
Index	0		1		2		...	

f_h 1442 % w → 2

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	null	0	...	...
Index	0		1		2		...	

Adding a Value

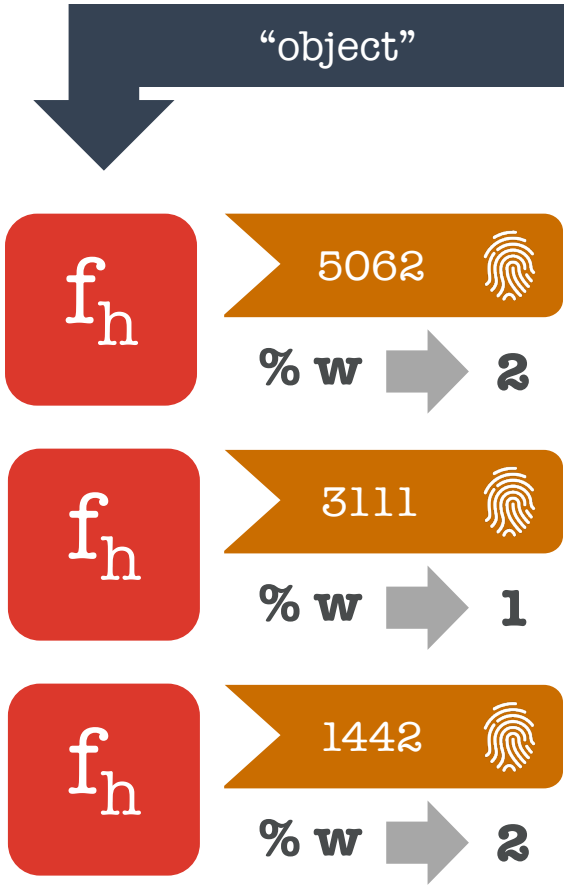


	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	**5062**	**1**	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	**3111**	**1**	null	0	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	**1442**	**1**	...	...
Index	0		1		2		...	

Adding the Same Value Again

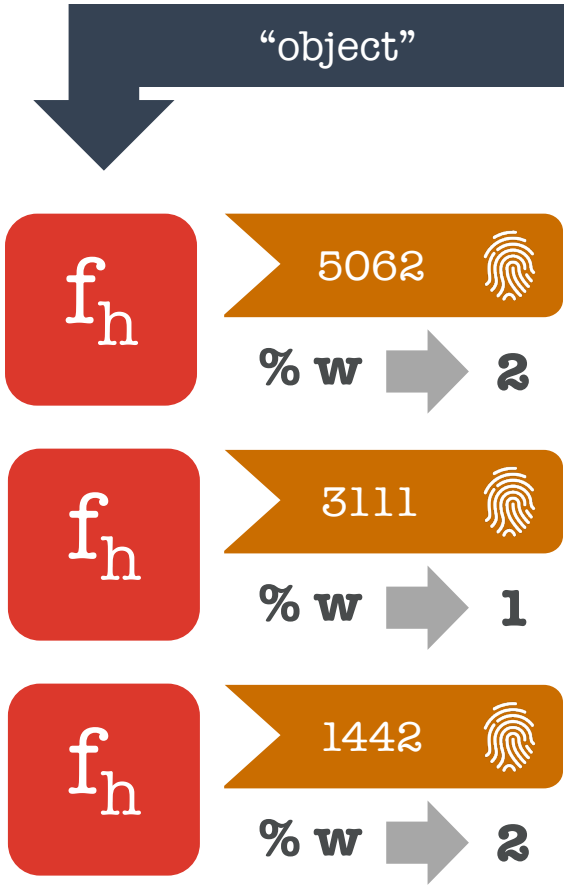


Bucket	null	0	null	0	5062	2	...	...
Index	0		1		2		...	

Bucket	null	0	3111	2	null	0	...	...
Index	0		1		2		...	

Bucket	null	0	null	0	1442	2	...	...
Index	0		1		2		...	

Querying the Count

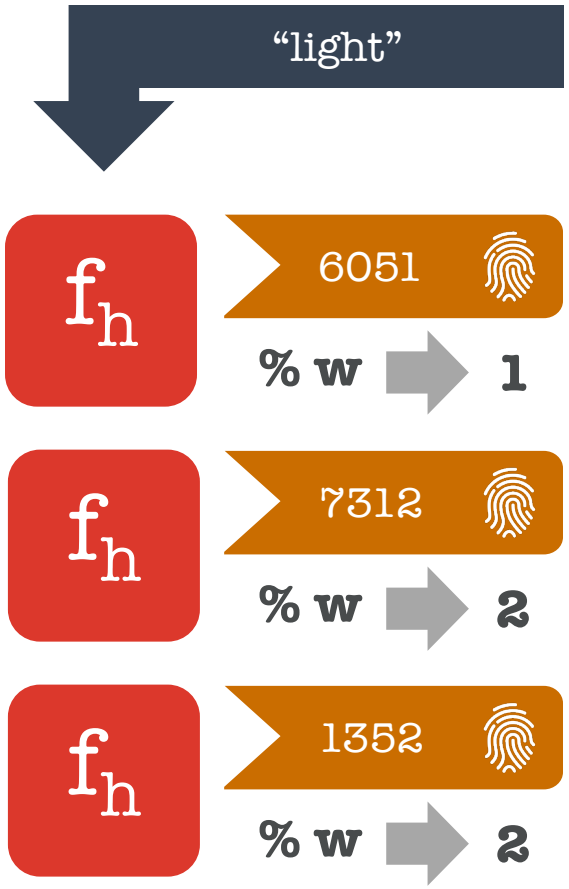


	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	**5062**	**2**	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	**3111**	**2**	null	0	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	**1442**	**2**	...	...
Index	0		1		2		...	

Adding a Different Value



	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	**6051**	**1**	5062	2	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	3111	2	**7312**	**1**	...	...
Index	0		1		2		...	

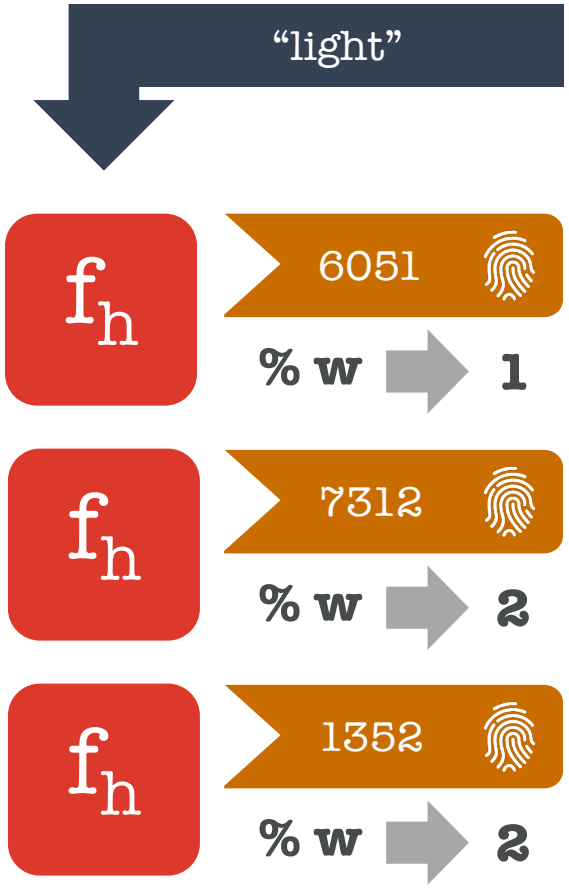
	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	**1442**	**2**	...	...
Index	0		1		2		...	

Probability of Decay

$$p = b^{-c}$$
$$p = 1.05^{-2}$$
$$p = 0.907$$

- $p \rightarrow$ probability of decay
- $b \rightarrow$ rate of decay
  - $-b > 1$
  - $-b \approx 1$
- $c \rightarrow$ the count

Decay Has Occurred

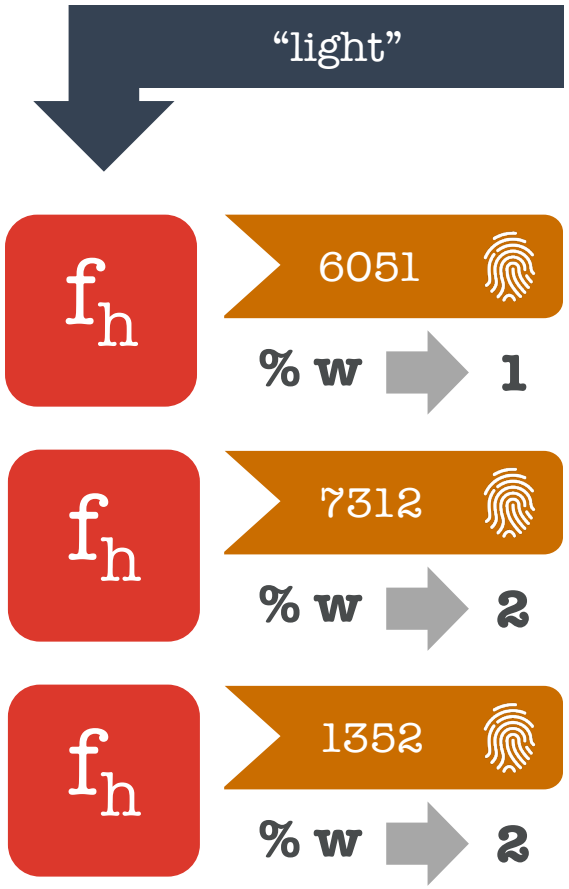


	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	6051	1	5062	2	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	3111	2	7312	1	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	**1442**	**1**	...	...
Index	0		1		2		...	

Querying After Decay

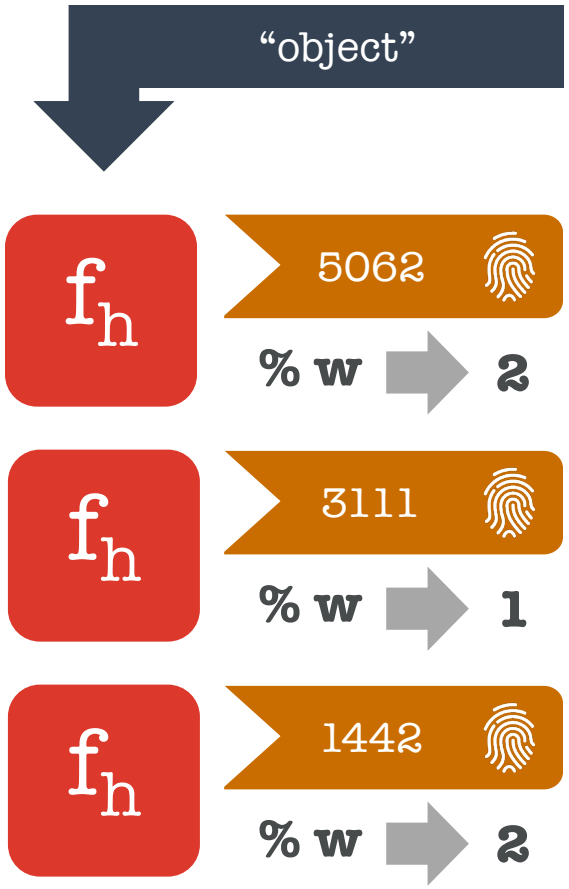


	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	**6051**	**1**	5062	2	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	3111	2	**7312**	**1**	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	1442	1	...	...
Index	0		1		2		...	

Querying the Count

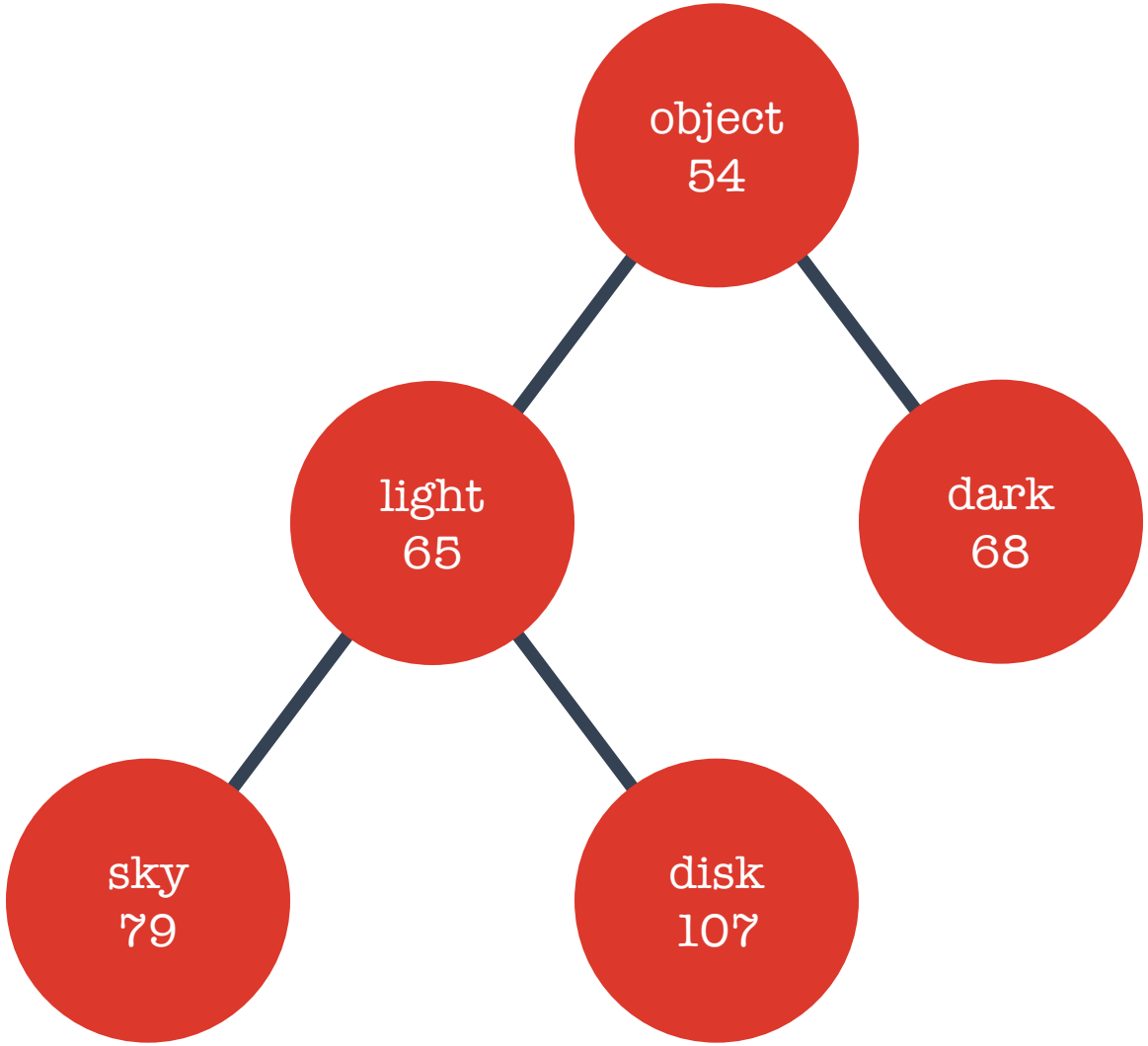


	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	**5062**	**2**	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	**3111**	**2**	null	0	...	...
Index	0		1		2		...	

	Hash	Count	Hash	Count	Hash	Count	Hash	Count
Bucket	null	0	null	0	**1442**	**1**	...	...
Index	0		1		2		...	

Updates the MinHeap Every Time



Using TopK in Redis

>	TOPK.RESERVE	ufo:shapes	3	100	5	0.9
	command	key	number	width	depth	decay
OK						

Adding to TopK in Redis

>	TOPK.ADD	ufo:shapes	disk
	command	key	Item to add
(nil)			

>	TOPK.ADD	ufo:shapes	disk	teardrop
	command	key	Item to add	Another item to add
(nil)				

>	TOPK.ADD	ufo:shapes	light	disk	teardrop
	command	key	Item to add	Another item to add	Another item to add
(nil)					

Using TopK in Redis

>	TOPK.QUERY	ufo:shapes	disk
	command	key	Item to add

```
(integer) 1
```

>	TOPK.COUNT	ufo:shapes	teardrop
	command	key	Item to add

```
(integer) 2
```

>	TOPK.LIST	ufo:shapes
	command	key

```
light
teardrop
disk
```


Demo

Resources

Bloom Filters by Example
https://llimllib.github.io/bloomfilter-tutorial/

Bloom Filter Calculator
https://hur.st/bloomfilter/

MinHash Tutorial
https://mccormickml.com/2015/06/12/minhash-tutorial-with-python-code/

HeavyKeeper: An Accurate Algorithm for Finding Top-k Elephant Flows
https://www.usenix.org/conference/atc18/presentation/gong

UFO Sightings Dataset
https://data.world/timothyrenner/ufo-sightings

The National UFO Reporting Center
http://www.nuforc.org/

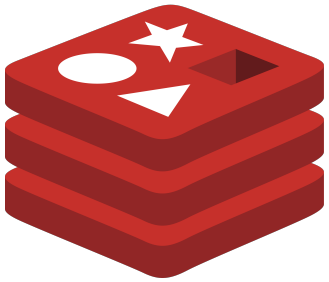
Redis Bloom
http://redisbloom.io/

Meet Top-K
https://redislabs.com/blog/meet-top-k-awesome-probabilistic-addition-redisbloom/

I Work For Redis Labs

Redis Discord Server

https://discord.gg/gmCACHU



Redis Community Forums

https://forum.redislabs.com/

Redis University

https://university.redislabs.com/

Code and Slides

https://github.com/guyroyse/understanding-probabilistic-data-structures

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Thanks!
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